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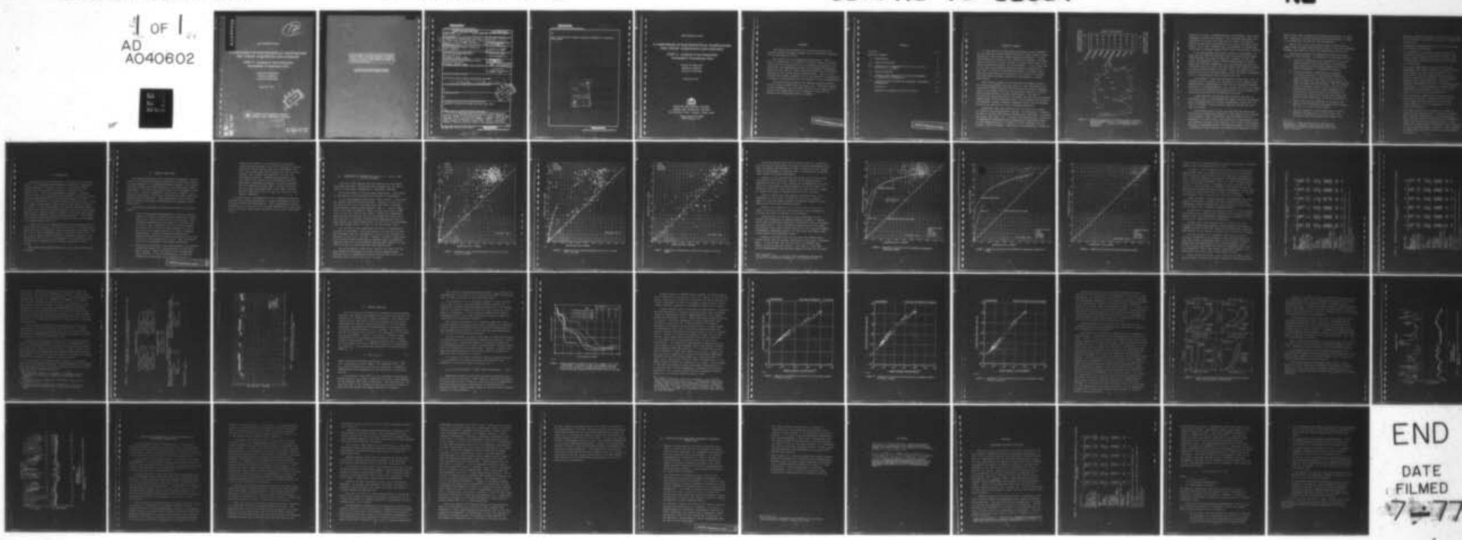

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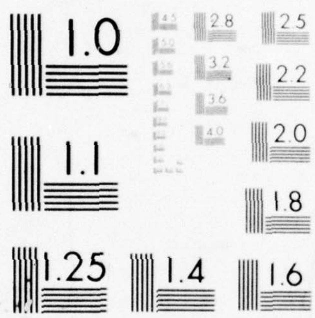

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A COMPARISON OF ELECTROOPTICAL TECHNOLOGIES FOR TARGET ACQUISITION AND GUIDANCE

PART 2: Analysis of the Grafenwöhr Atmospheric Transmission Data

Lucien M. Biberman
Robert E. Roberts
Lynne N. Seekamp

January 1977

INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION

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In 1975 an ARPA/EUCOM-sponsored Battlefield Target Acquisition Symposium raised questions about electrooptical sensor performance in the winter weather of Central NATO Europe. In response, DDR&E and ARPA launched a set of field trials at Grafenwöhr, Germany. This two-part report presents the findings of those trials. Part 1, classified, presents to DOD activities the results of the equipment evaluations.

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A COMPARISON OF ELECTROOPTICAL TECHNOLOGIES FOR TARGET ACQUISITION AND GUIDANCE

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FOREWORD

This report was prepared for the Deputy Director for Tactical Warfare Programs, ODDR&E, and is especially addressed to the Land Warfare Office.

The report is in two separately bound parts. Part 1, which is classified, is intended to provide technical guidance for policy and planning and is not a detailed dissertation on scientific and engineering effects and atmospheric phenomena, since the data from the tests described therein is still being analyzed at the various Service laboratories. Part 2, this unclassified volume, presents data on the results of atmospheric transmission measurements and is intended for wider dissemination.

The work was supported by the Defense Advanced Research Projects Agency (ARPA) under IDA Task A-38. Detailed analysis of the atmospheric data is being carried out in support of an optical and submillimeter wave propagation study for the Research and Technology Office of ODDR&E.

CONTENTS

EXECUTIVE SUMMARY

In June 1975 the United States European Command (USEUCOM) and the Defense Advanced Research Projects Agency (ARPA) jointly sponsored a "Battlefield Target Acquisition Seminar." During this seminar the problem of the relative performance of electro-optical sensors in weather typical of Central NATO Europe occupied a substantial portion of the discussion. It was clear that in the past some advanced technology weapons systems did not fare well in trials in the Federal Republic of Germany (FRG). Questions arose about the suitability of a number of proposed and developmental weapon systems for the defense of Central NATO Europe.

The Principal Deputy to the Director of Defense Research and Engineering (DDR&E) was made aware of this discussion, and consequently DDR&E requested the Institute for Defense Analyses (IDA) to recommend a plan for evaluating the effects of Central NATO European weather on system performance. The task of executing the plan was given to the Army, with the Army Electronics Command Night Vision Laboratory (NVL) of the Materiel Development and Readiness Command (DARCOM) designated as the executive agent, and with the Navy and Air Force providing assistance.

Grafenwöhr, FRG, was chosen as the test site for a number of logistic and meteorological reasons. An examination of weather records of Central NATO Europe indicates that Grafenwöhr represents the region well (Fig. S-1). Further, the meteorological conditions as measured at Grafenwöhr occur frequently at many other places in the temperate world, i.e, Camp A.P. Hill, Virginia, and the southern coast of England. When similar meteorological conditions

26 Nov - 15 Jan 1975/76

VISIBILITY RANGE LESS THAN OR EQUAL TO (KM)	DUESSELDORF	WIESBADEN	BREMEN	KITZINGEN	GRAFENWOEHR	DRESDEN	PRAGUE	LINZ	VISIBILITY RANGE LESS THAN OR EQUAL TO (KM)
10	62	58	57	58	69	91	64	79	10
7	41	46	40	41	51	78	42	65	7
5	31	27	30	16	31	56	25	54	5
2	10	7	7	2	7	23	7	24	2

1-28-77-4

FIGURE S-1. Cumulative Frequencies of Visibility Ranges at Central European Weather Stations, and Geographical Locations of the Stations. (Source: U.S. Army Night Vision Laboratory)

occur at A.P. Hill, southern England, or Grafenwöhr, the optical propagation effects are similar. The frequency with which the conditions occur may vary from place to place, but there is nothing unique about the physics of the winter Grafenwöhr atmosphere. It is true, however, that the frequency of unfavorable conditions is somewhat greater there than in many other locations.

As no measurements were made in summer at Grafenwöhr, we have used the USAF Environmental Technical Applications Center (ETAC) weather data base for Hannover, Germany, in 1970 as a source of atmospheric data on Central NATO Europe in summer. Based upon the ETAC statistics, our calculations show absolute humidities around 13 g/m^3, but they rarely show extended periods of high relative humidity and fogs. Thus, the summer would be expected to bring a lowered maximum value of infrared transmission due to increased water vapor and much less fog.

The program of tests was formulated in early fall 1975, but DARCOM could not complete all the details of the financial and administrative arrangements in time for the scheduled November beginning of the measurements. As a result only the least expensive and least logistically complicated part of the program was tentatively approved for the desired time frame.

A team from NVL with appropriate equipment was sent to Grafenwöhr, FRG, in mid-November and began producing atmospheric data, including data on infrared transmission, during the last week of November. This activity continued through the first week in January.

During this period the raw recorded data was photocopied from field notebooks and forwarded to IDA, where it was reduced and evaluated. Small corrections were introduced into the programs at an early phase, and production of high-quality data was achieved for most of the program. Of a total of 678 hourly samples of atmospheric data, 214 excellent samples were obtained in moderately clear weather, 154 samples were obtained in snow

and/or rain, and 54 samples were obtained in moderate to heavy fog. Because of various unexplained inconsistencies, 256 sets of raw data were not used for the IDA analysis.

The results of the tests were briefed in April 1976 to DDR&E, ARPA, and the three Services, and in June 1976 to USEUCOM, USAREUR, and USAFE by a team from ARPA-Europe, NVL and IDA.

This report presents a somewhat more formal and final version of that briefing. We summarize our conclusions below:

1. Collected atmospheric data confirms that it is the aerosol content of the atmosphere, not humidity, that imposes the most severe limitation on atmospheric propagation at Grafenwöhr in winter.
2. The meteorological conditions at Grafenwöhr in winter give rise to low *absolute* humidities characterized by dew points of -15° to 0°C (1-5 grams of water per cubic meter of atmosphere), but high (70-100%) *relative* humidity. The low *absolute* value of humidity results in very little loss of transmission due to water vapor absorption, but high *relative* humidity favors the formation of haze and fog, which often become quite dense and become severe limitations to optical propagation.
3. Under clear winter conditions we calculate and measure little difference in transmission between the 3.4-4.1 μm and 8-12 μm* bands.
4. When the weather is sufficiently bad to reduce measured transmission at 1 km to 10% in the television and near-visible laser bands, the

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*We refer to these bands as 3-5 μm and 8-12 μm generically. Ideally, the 8.5-11 μm band is a best choice for many IR applications, as is the 3.4-4.1 μm band.

measured infrared transmission in the 3.4-4.1 μm and 8-12 μm bands is still well in excess of 50% and 60%, respectively.

5. Atmospheric transmission in the 1.06 μm laser band suffers badly with weather.

6. The degradation of image contrast propagation is equal for all bands in either rain or snow. This implies that a trivial scaling law could be used to extrapolate visibility data into the IR regions for these cases.

7. Both field measurements, such as those taken at Grafenwöhr, and theory establish a strong relationship between the total volume content of the particulate along the transmission path and the aerosol extinction coefficient. This observation suggests that a phenomenological scaling of photopic transmission (related to the meteorological visibility) to the IR windows is possible, which furthermore is independent of the structure or shape of the particle size distribution.

8. Our work further implies that a simple quantity relating the volume to the mass of the aerosol (i.e., grams per cubic meter) could provide a direct measure of the IR transmission (an IR "visibility meter").

9. Much data analysis still remains to be done to establish the precise degree to which calculations match measured transmission, but it seems clear that existing models for predicting the transmission effects due to molecular absorption are in good shape, with some dubious coefficients still remaining in the 3-5 μm water vapor continuum. Rapid progress is being made in aerosol modeling, but much remains to be done.

I. INTRODUCTION

The purpose of this second part of our report is to review some of the transmission measurements conducted at Grafenwöhr, Federal Republic of Germany, by the U.S. Army Night Vision Laboratory (NVL) during the period from November 1975 to January 1976. Since the measurements represent a temperate winter climate, our discussion and subsequent conclusions apropos of sensor performance will be directed primarily at aerosol effects representative of Central European fogs and hazes. There is a common misconception about relative and absolute humidity in Europe. In the German winter the absolute humidity tends to be quite low, while the relative humidity tends to be quite high. High relative humidity favors formation of mist and haze, while high absolute humidity absorbs infrared radiation. The subject of broadband infrared water vapor absorption has been discussed in a separate paper (Ref. 1).

In this part of our paper we examine the atmospheric data in three bands of interest. The first is the 0.8-1.1 μm band that spans the active television, the silicon-vidicon television, and the 1.06 μm laser designator bands. The second band is the 8.1-12.1 μm band for FLIR design and evaluation purposes. The third band, 3.4-4.1 μm, is of interest for an alternative form of FLIRs that probably will be of major importance in the future.

These data were measured every hour over a path 1180 meters in length.

II. SCOPE OF DATA BASE

The stated objective of the first-phase atmospheric measurements was "to measure broadband transmission in spectral regions of prime interest to the image development community over significant path lengths and under frequently occurring meteorological conditions." The data could then be used as a "broadband validation check on current atmospheric codes such as LOWTRAN 3 and provide a data base of real-world transmissions under quantified meteorological conditions." This measured data could then be used to validate the sensor performance models against actual field tests.

The measured atmospheric parameters consisted of the following:

1. Hourly transmission measurements in selected spectral bands for a 1180-m horizontal ground path and a 4310-m slant path (from a 125-ft tower to the ground). The condensed transmission data, taken on a routine basis 24 hours a day, consisted of 0.8-1.1 μm (Si detector for active TV), 3.4-4.1 μm (InSb detector for FLIR), and 8.1-12.0 μm (HgCdTe detector for FLIR) broadband measurements. Several selected narrow-band and special-interest spectral channel measurements were also included in the expanded set of data. The instruments used in this experiment were Barnes radiometers.

2. Simultaneous recording of the meteorological and physical parameters thought to be most pertinent to the atmospheric models. These included multiple measurements (four stations) of the air temperature and relative humidity at points along the transmission path. A

subjective estimate of the visibility and weather conditions was provided by the Army Atmospheric Sciences Laboratory meteorological team at the Grafenwöhr test site, and similar data were obtained from the Air Force weather tower located approximately 5 km from the experimental station. Additional measurements were also made of the aerosol size distribution [with the HeNe laser scattering instrument of the Knollenberg Particle Measuring System (PMS)], optical dew point, wet bulb-dry bulb temperatures, total water content, gaseous composition (CO_2, CO, N_2O, O_3, and CH_4), and aerosol chemistry.

In this volume on atmospherics we will emphasize primarily what has been learned appropriate to sensor performance from the condensed ground-path measurements. More comprehensive reports detailing all of the above will be made available at a later date, both by the Army Night Vision Laboratory and by IDA in IDA Paper P-1225.

III. COMPARISON OF TRANSMISSION IN 0.8-1.1, 3.4-4.1, AND 8.1-12.1 μm BANDS

The first three figures show the unsorted raw Grafenwöhr data resulting from a processing that included only the application of instrument calibration to instrument readings.

We believe Figs. 1-3 are the most significant. The numbers on the points in the plots show the sequence of measurement.

It is quite apparent that there is much scatter in the data--all weather conditions being included. However, if one plots the data in the 8.1-12.1 μm band versus the 0.8-1.1 μm band, three separate groups become apparent (Fig. 1). One set represents data taken in medium to heavy fog and lies along a steep curve on the left side of the figure. Another set represents data obtained in snow and rain and lies along the 45-deg line. The third set is the mass of data points representing clear to hazy weather and lying between about 0.6 and 0.8 on the horizontal scale and between about 0.75 and 1.0 on the vertical scale.

One can draw a line along which the value of transmission is equal in two bands. All points above or to the left of that line indicate that the transmission in the 8.1-12.1 μm band is superior to the 0.8-1.1 μm band. Clearly, the mass of data lies in a cloud of points positioned to indicate that, as might be expected, the 8.1-12.1 μm infrared band <u>is</u> often superior to the 0.8-1.1 μm band of television and laser applications.

The second thing is that in the majority of cases for this path length of 1180 meters in clear to hazy conditions the average value of transmission is about 0.9 for the 8.1-12.1 μm band and about 0.65 for the 0.8-1.1 μm band.

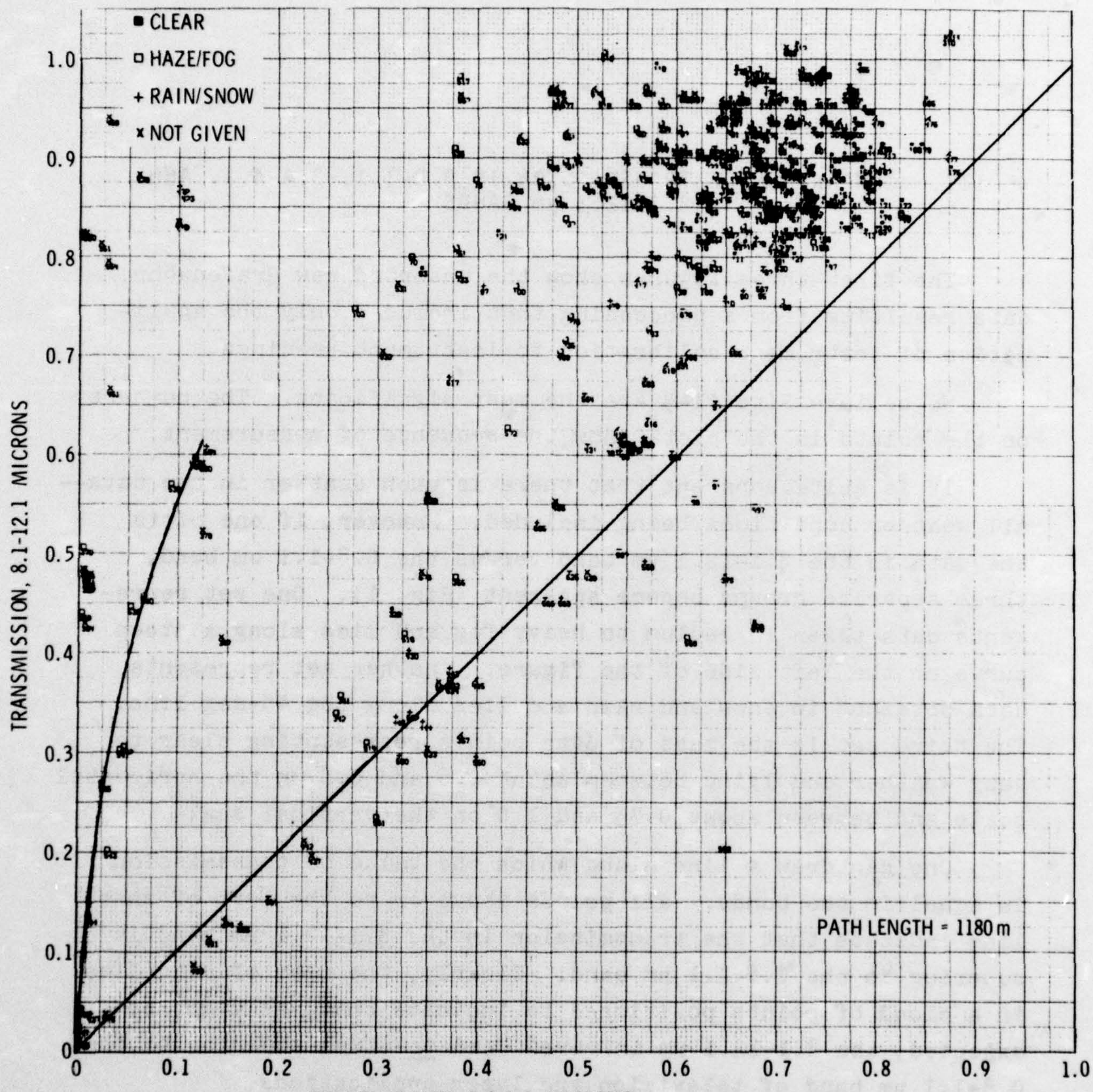

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FIGURE 1. Comparison of Raw Transmission Data in the 0.8-1.1 μm and 8.1-12.1 μm Bands

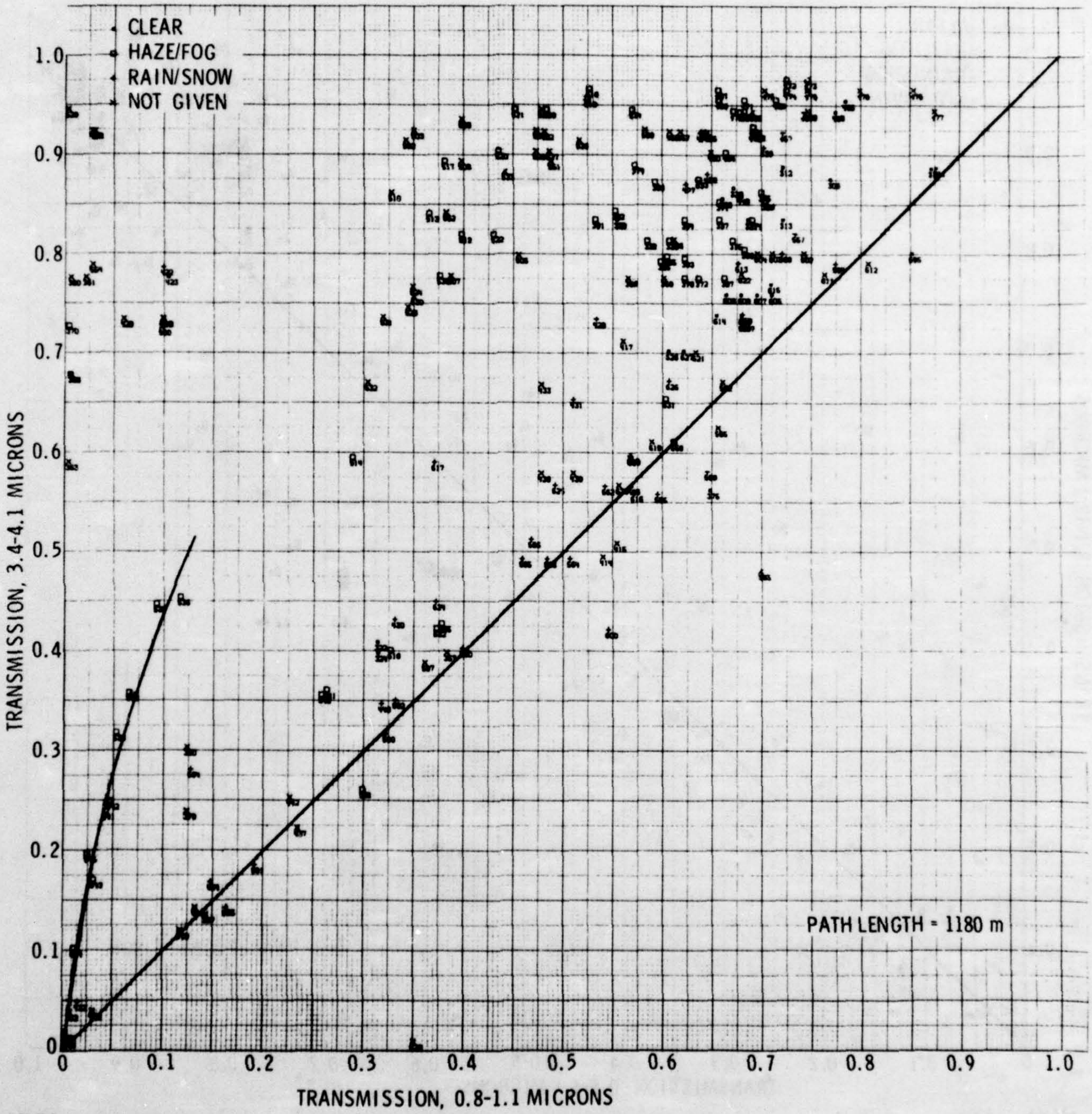

FIGURE 2. Comparison of Raw Transmission Data in the 0.8-1.1 μm and 3.4-4.1 μm Bands

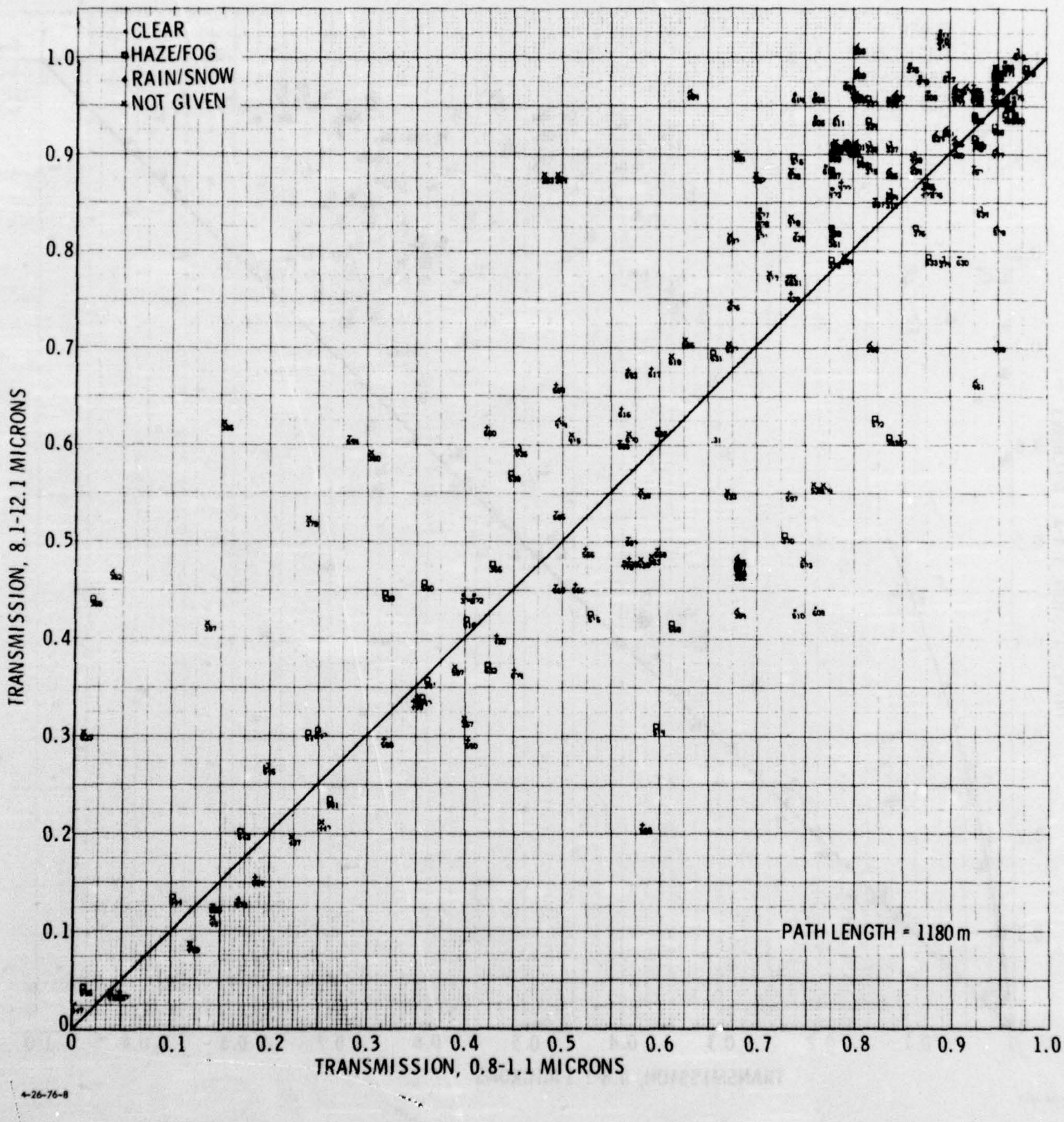

FIGURE 3. Comparison of Transmission in the 3.4-4.1 versus 8.1-12.1 μm Bands

The third factor which can be noted is that for conditions of rain and snow the points lie along the equal-transmission line. That is because the particles of rain or snow are so much larger than the wavelengths of interest that the attenuation is approximately equal for those wavelengths.

Lastly, if one can read the fine print on the points along the steep curve at the left, one can follow numbers almost sequentially down the curve, showing the transmission in the two bands as a fog builds up during December 30 and 31, 1975. It should be noted that this curve shows that the 8.1-12.1 μm band is nearly six times as favorable as the 0.8-1.1 μm band.

Figure 2 shows that very similar conditions exist in a comparison of the 3.4-4.1 μm band and the 0.8-1.1 μm band. Again, in fogs the middle infrared is markedly superior to the near-visible laser and television bands.

Figure 3, a comparison of the 3.4-4.1 and 8.1-12.1 μm bands, essentially points up the equality of the transmission in these two bands in moderate to good weather.

Unfortunately for the work in the second phase of the trials--the comparison of imagery systems, troubles of various sorts made the measured atmospheric transmission data both sparse and questionable. Thus, alternative measures had to be taken. Fortunately, there was a backup available in the improved LOWTRAN atmospheric transmission model,* on which work had begun almost a year before the Grafenwöhr trials.

Figures 4 through 6 show the raw data and LOWTRAN calculations based upon the weather conditions at the times of measurement. It can be seen that the plot from the LOWTRAN model passes nearly through the center of the swarm of trial data points representing clear and hazy weather, but as yet the model

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*The LOWTRAN 3 model of the Air Force Geophysics Laboratory, as well as the improved LOWTRAN 3a, is discussed in Ref. 2.

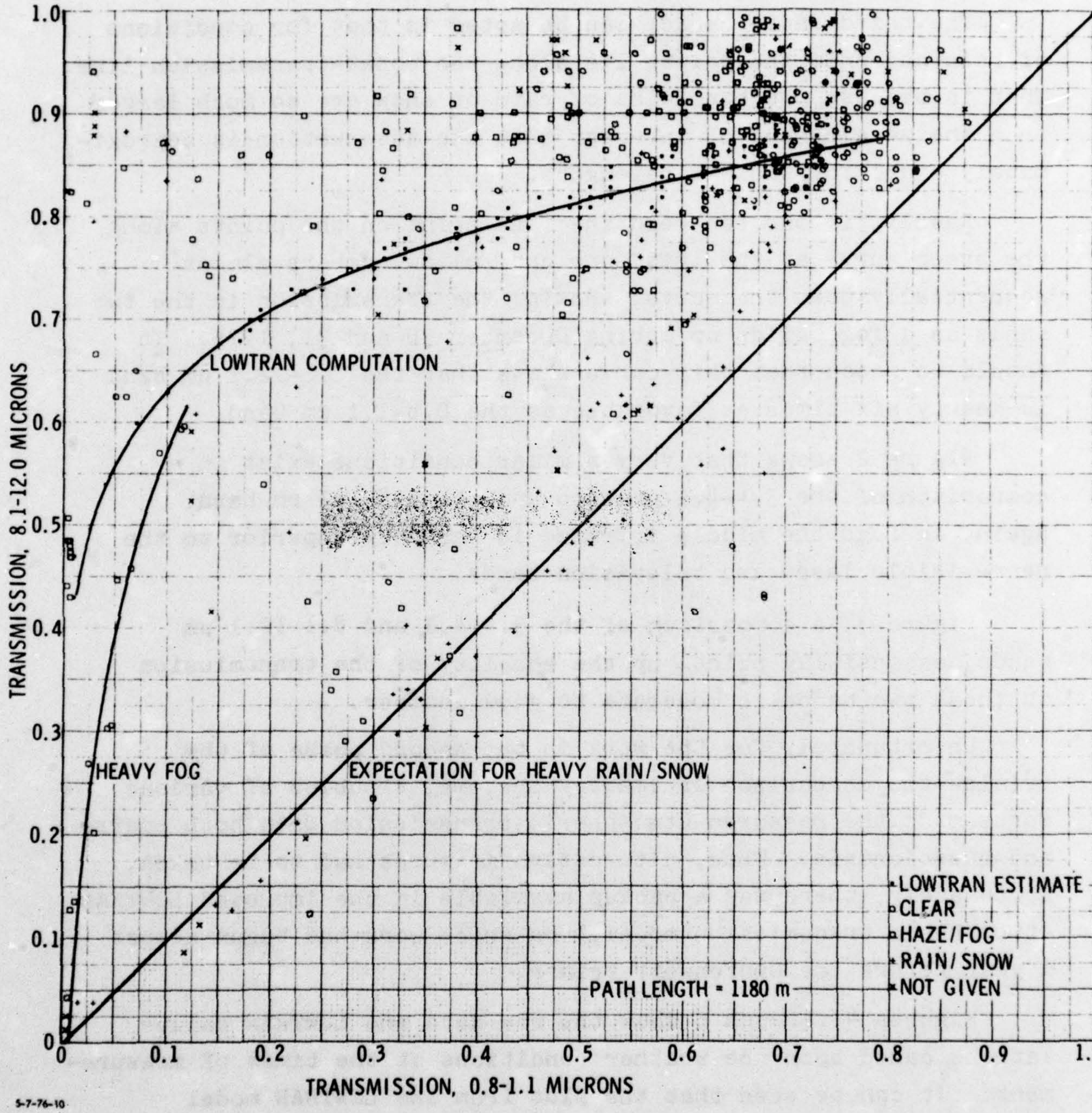

FIGURE 4. Comparison of Raw Data with the LOWTRAN 3a Atmospheric Transmission Model

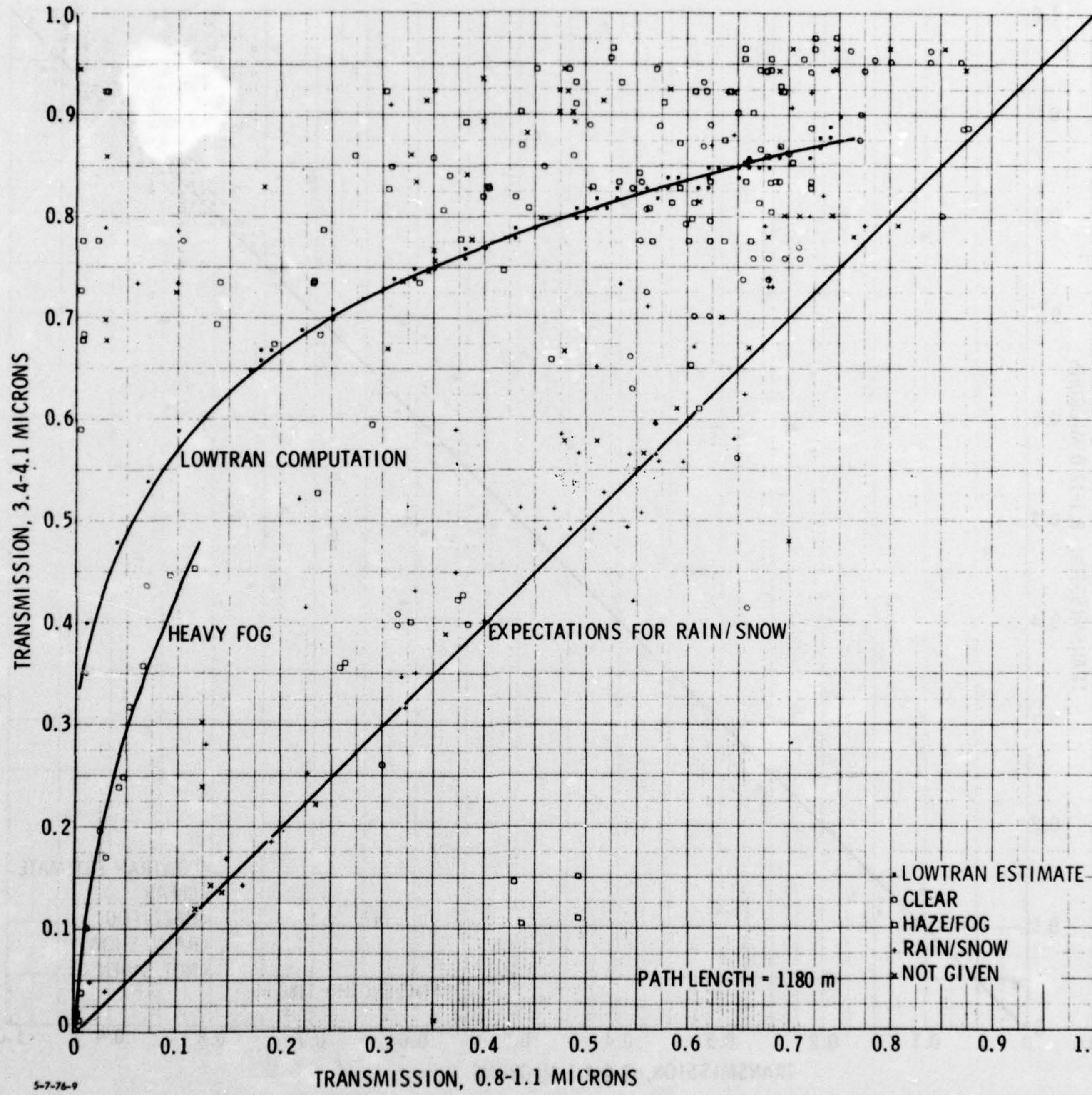

FIGURE 5. Comparison of Raw Data with LOWTRAN 3a Atmospheric Transmission Model

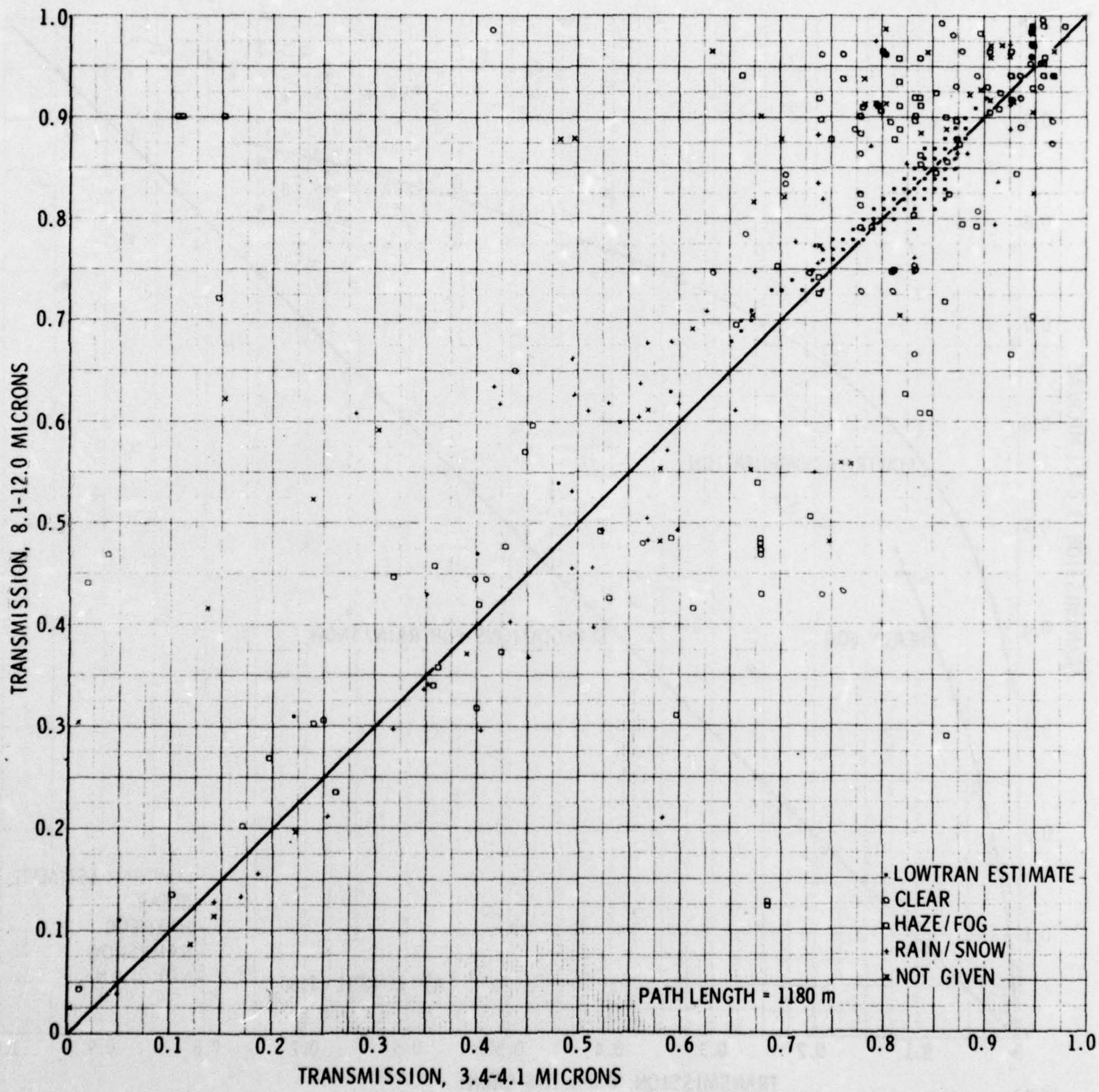

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FIGURE 6. Comparison of Raw and Calculated Transmission Data

does not match the measured data for heavy fog very well, yielding results that are significantly too high.

In Figs. 4 and 5 we see that the effects of heavy rain and snow neither favor nor penalize any band relative to any other. The rain and snow data points lie along the equal transmission line. When the weather is bad enough to reduce transmittance to 10% in the TV and laser band (0.8-1.1 μm), the IR transmittances in the 3.4-4.1 and 8.1-12.1 μm bands are still well above 50%. In Fig. 6, both theoretical (LOWTRAN) calculations and experimental data lie near the line of equal transmission. Thus, there is little in these winter data to cause a preference for one of the IR bands (3.4-4.1 μm, 8.1-12.1 μm) over the other.

There is always a certain spread in experimental data that makes it difficult to compare them with theoretical results. Differences between measured data and theoretical results may be real or may be due to scatter in measured data.

We therefore compared the measured data in all three bands, the visibility as computed from measured silicon band transmissometer data, and the infrared transmission as computed on the basis of the components of the atmosphere.

Perhaps 30% of the measured data is "wild" due to the category of operational problems, perhaps another 30% ranges somewhat beyond ±10-15% from theoretical computations, and perhaps another 30% is tightly clustered about theoretical results.

To sort the data in a consistent way, we set up seven criteria, explained in the appendix, that would segregate the data into various categories, each of which could be examined separately. The application of all seven exclusion rules to the 670 data sets yields 213 sets of acceptable useful data in a category we term "good weather conditions," which is not synonymous with crisp, clear, ideal winter weather.

Tables 1a and 1b are two runs of sets of good data, showing the kinds of spread that exist between the measured data and

TABLE 1a. COMPARISON OF MEASURED AND CALCULATED TRANSMISSION FOR 1180-METER PATH LENGTH

SEQUENCE NUMBER	41	43	44	54	60	66
DATE	11/30/75	11/30/75	11/30/75	12/ 1/75	12/ 1/75	12/ 1/75
TIME	1046	1246	1330	100	700	1300
PRESSURE (MB)	951	952	952	957	961	964
TEMPERATURE (C)	1.7	3.2	2.9	2.3	1.9	2.8
REL.HUMIDITY (PCT)	98	95	96	99	99	98
WATER VAPOR DENSITY (GM/M3)	5.34	5.72	5.67	5.61	5.46	5.75
WEATHER TYPE (1A)[a]	LTFG[b]	--	--	LTFG[b]	LTFG[b]	LTFG[b]
WEATHER TYPE (3A)[c]	HAZE	HAZE	HAZE	LTFG[b]	LTFG[b]	LTFG[b]
VISIBILITY (KM):						
ASL[d]	7.0	5.5	4.5	3.7	4.0	1.5
AF[d]	11.2	11.2	8.0	3.4	4.0	2.6
SILICON[d]	6.5	12.5	14.1	A[e]	6.5	6.4
PHOTOPIC[d]	4.4	8.4	9.5	2.6	4.4	4.3
NON-AEROSOL[d]	4000.	4000.	4000.	4000.	4000.	4000.
TRANSMISSIONS:						
MEASURED	.884	.872	.872	.822	.877	.833
ASL LOWTRAN[d]	.837	.816	.802	.785	.795	.654
AF LOWTRAN[d]	.858	.852	.839	.777	.795	.743
Si LOWTRAN[d]	.833	.855	.860	A[e]	.831	.825
PHOTOPIC LOWTRAN[d]	.805	.840	.846	.748	.803	.797
NON-AEROSOL LOWTRAN[d]	.893	.886	.887	.887	.890	.885
EXTINCTION COEFFICIENT (KM^{-1})						
MEASURED	.105	.116	.116	.166	.111	.155
NON-AEROSOL[d]	.096	.102	.102	.101	.099	.104
ESTIMATED AEROSOL EXTINCTION (KM^{-1})	.009	.014	.014	.065	.012	.051

[a] 1A = subjective estimate of NVL personnel at transmissometer site.

[b] LTFG = light fog.

[c] 3A = subjective estimate of ASL personnel along transmissometer path.

[d] Term explained in appendix.

[e] A = not calculated.

TABLE 1b. COMPARISON OF MEASURED AND CALCULATED TRANSMISSION FOR 1180-METER PATH LENGTH

SEQUENCE NUMBER	114	115	116	117	118	120
DATE	12/ 3/75	12/ 3/75	12/ 3/75	12/ 4/75	12/ 4/75	12/ 4/75
TIME	2200	2300	2356	100	200	400
PRESSURE (MB)	964	965	966	967	968	969
TEMPERATURE (C)	3.9	3.6	3.1	2.2	2.0	1.0
REL. HUMIDITY (PCT)	90	88	94	97	98	99
WATER VAPOR DENSITY (GM/M^3)	5.68	5.45	5.63	5.46	5.45	5.14
WEATHER TYPE (1A)[a]	CLER[b]	CLER[b]	CLER[b]	CLER[b]	CLER[b]	CLER[b]
WEATHER TYPE (3A)[c]	CLER[b]	HAZE	HAZE	HAZE	CLER[b]	CLER[b]
VISIBILITY (KM):						
ASL[d]	5.0	14.0	14.0	5.0	10.0	5.0
AF[d]	11.2	11.2	11.2	11.2	11.2	11.2
SILICON[d]	15.9	15.2	12.8	11.0	9.7	7.3
PHOTOPIC[d]	10.7	10.3	8.7	7.4	6.6	4.9
NON-AEROSOL[d]	4000.	4000.	4000.	4000.	4000.	4000.
TRANSMISSIONS:						
MEASURED	.859	.793	.870	.859	.793	.859
ASL LOWTRAN[d]	.811	.864	.860	.813	.852	.818
AF LOWTRAN[d]	.853	.857	.853	.856	.856	.861
Si LOWTRAN[d]	.863	.866	.858	.855	.850	.842
PHOTOPIC LOWTRAN[d]	.851	.854	.843	.838	.831	.817
NON-AEROSOL LOWTRAN[d]	.887	.892	.888	.890	.890	.896
EXTINCTION COEFFICIENT (KM^{-1}):						
MEASURED	.129	.196	.118	.129	.196	.129
NON-AEROSOL[d]	.101	.097	.101	.099	.098	.093
ESTIMATED AEROSOL EXTINCTION (KM^{-1})	.028	.099	.017	.030	.098	.036

[a] 1A = subjective estimate of NVL personnel at transmissometer site.

[b] CLER = clear.

[c] 3A = subjective estimate of ASL personnel along transmissometer path.

[d] Term explained in appendix.

four sets of LOWTRAN calculations that occur when things are going well. Note that the transmission tends to average about 0.85 for the ground-level 1180-meter path. The difference between measured data and the ASL LOWTRAN*, AF LOWTRAN*, Si LOWTRAN* and photopic LOWTRAN* averages are about 0.01 (Table 1c). In measurement sequence 66, there is good agreement with measured transmission only by computed Si LOWTRAN transmission** and computed photopic transmission***. Note that the observations by the Army Atmospheric Sciences Laboratory (ASL) meteorological team and the Air Force (AF) meteorological tower show a serious deviation. At present we can point out these facts but can offer no explanation.

Note also that in Table 1b in sequences 115 and 118 the measured data vary by 0.06 from the computed data. It seems that in what we term well-behaved data sets the spread between measured and computed data is about 3% for about 85% of the time but exceeds 6% for about 15% of the time.

Because the fine scale and structure of the data would be lost or obscured by reduction of a graphic representation of all of it to a size suitable for the printed page, we have chosen to show data over a span of only a few days. Figure 7 shows a plot of transmission as measured and as computed from four different data inputs. It is clear that the model for calculation of transmission in this infrared region is relatively good.

The fog model is a separate case and will, it is hoped, result from the completed analysis of the Grafenwöhr data together with other data from the Air Force Geophysics Laboratory and the Army Atmospheric Sciences Laboratory.

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* The terms ASL LOWTRAN, AF LOWTRAN, Si LOWTRAN, photopic LOWTRAN, and non-aerosol LOWTRAN are explained in the appendix.

** Computed by using LOWTRAN and "visibility" from silicon transmissometer.

*** Computed by using LOWTRAN and "visibility" from silicon transmissometer, extrapolated to the 0.55 μm visible range.

TABLE 1c. COMPUTED AND MEASURED 8.1-12.1 μm TRANSMISSION STATISTICS FOR "GOOD WEATHER" OVER A 1180-METER PATH LENGTH

Computed Transmission Data

ASL LOWTRAN* Transmission:

No. of Samples	184
Average Transmission	0.85
Standard Deviation	0.05

AF LOWTRAN* Transmission :

No. of Samples	212
Average Transmission	0.85
Standard Deviation	0.07

Si LOWTRAN* Transmission:

No. of Samples	176
Average Transmission	0.87
Standard Deviation	0.02

Photopic LOWTRAN* Transmission:

No. of Samples	176
Average Transmission	0.86
Standard Deviation	0.03

Measured Transmission Data

No. of Samples	214
Average Transmission	0.84
Standard Deviation	0.05

Comparison of Computed and Measured Data

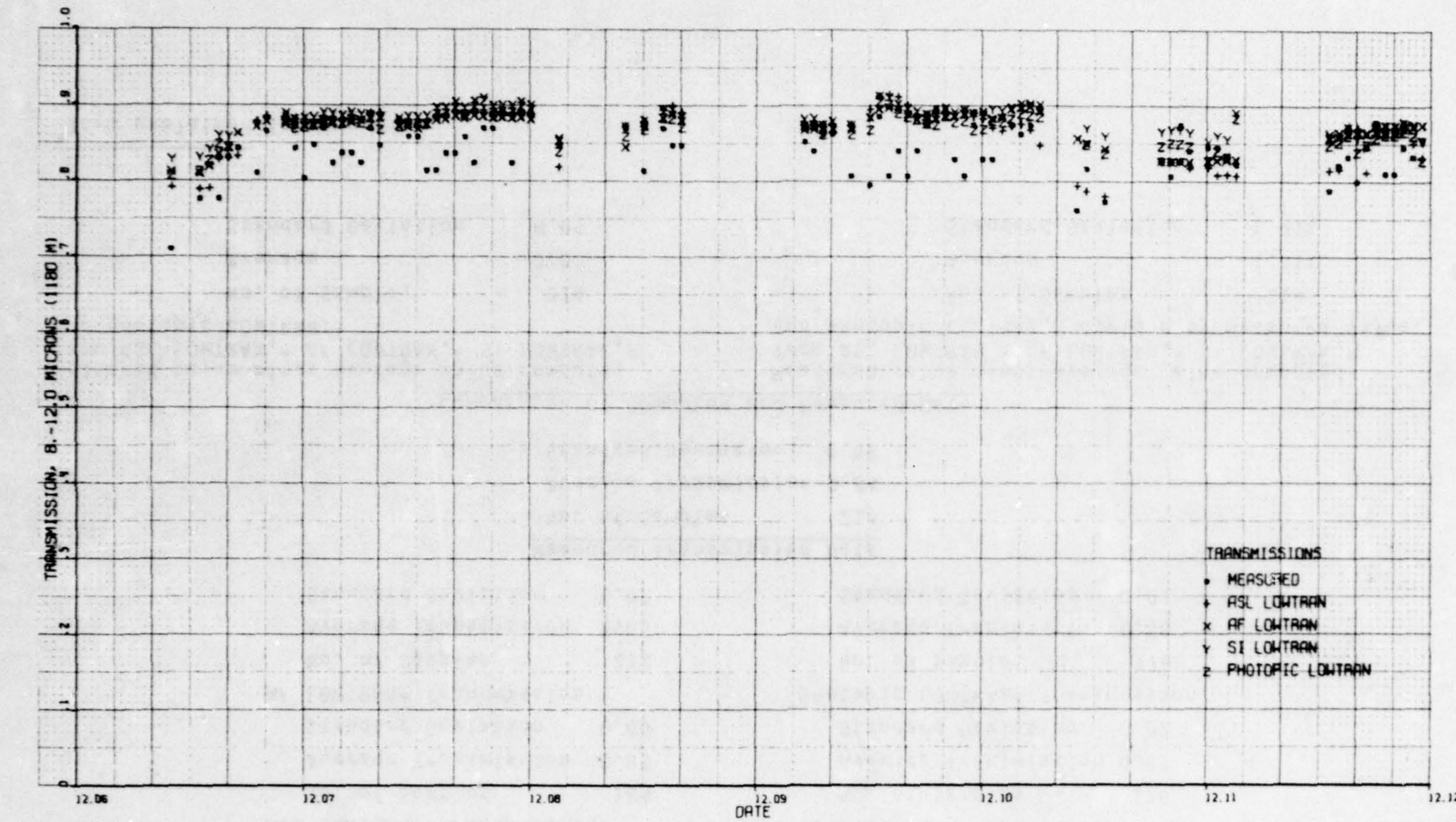
Measured value minus average value computed from ASL LOWTRAN,* AF LOWTRAN,* Si LOWTRAN,* and photopic LOWTRAN:*

No. of Samples	214
Average	-0.01
Standard Deviation	0.06

Measured value minus average value computed from ASL LOWTRAN,* AF LOWTRAN,* Si LOWTRAN,* and photopic LOWTRAN,* divided by measured value:

No. of Samples	214
Average	-1.41%
Standard Deviation	6.71%

*Term explained in appendix.



8-18-76-3

FIGURE 7. Comparison of Measured and Calculated Transmissions, Dec. 6-12, 1975, Ground Level, Grafenwöhr

IV. AEROSOL MODELING

To be of use in the operational planning of electrooptical missions, our weather measurements and forecasting must have the capability of predicting IR image propagation. This means that either we must make better use of our present data collection techniques with updated transmission models or we must determine which new meteorological measurements are necessary for an improved understanding of the IR windows. Two separate and distinct mechanisms are involved in the attenuation of infrared and optical signals. That is, the amount of radiant energy transferred by the atmosphere is determined by two principal types of constituents: (1) gaseous molecules and (2) aerosols or particulates, with their respective extinction coefficients σ_{mol} and σ_{aer}. At a particular wavelength the transmission is given by

$$T = \exp(-\sigma_{tot} L) \tag{1}$$

where the total extinction coefficient is $\sigma_{tot} = \sigma_{mol} + \sigma_{aer}$, and L represents the path length. The magnitude of σ_{mol} or σ_{aer} clearly depends upon the optical properties, atmospheric concentration, and temperature of the molecular or particulate species.

In a previous paper (Ref. 1), the problems of determining proper values of σ_{mol} were covered in some detail, with emphasis on the dominant water vapor attenuation. The conclusion of that paper was that in the absence of significant aerosol effects a more realistic sensor performance analysis is possible.

The problem of predicting better values of σ_{aer} remains outstanding and is the subject of a current study under the sponsorship of DDR&E (Research and Advanced Technology).

The findings of Ref. 1 are based largely on data from EMI Ltd., Camp A.P. Hill, and Grafenwöhr and have resulted in a method for predicting aerosol extinction based upon a knowledge only of the aerosol composition and its total volume per cubic meter of atmosphere. If this method is indeed valid, and we strongly believe it is, then it should be carefully tested for electrooptical forecasting purposes.

The critical hypothesis to be tested is that *for a particular aerosol and spectral region the attenuation or extinction is most critically dependent upon the volume of particulate in the atmopsheric path and not so much upon the detailed description of its size distribution function.*

If this statement is valid (as we hope to demonstrate below), the ramifications to the modeling community are manifold. First, it implies that a simple measurement of a quantity related to the transmission path (i.e., g/m^3) could provide a direct measure of the IR transmission characteristics. Second, it leads to an improved modeling technique for scaling visible transmission data into the IR regions of interest.

For example, the above assertions can be ultimately reduced to an equation that relates extinction coefficient in the infrared to one in the visible spectrum, i.e.,

$$\sigma_{aer} \text{ (long wavelength)} \sim \sigma_{aer}^{1.50} \text{ (short wavelength)} \quad . \qquad (2)$$

Measurements made at Grafenwöhr during the buildup of fog at ground level establish a firmer basis for modeling fog effects. It can be seen in Fig. 8 that as a fog rolls in and transmission and visibility grow poorer and poorer, the distribution of particles shows a marked change toward an increase in the relative fraction of large droplets.

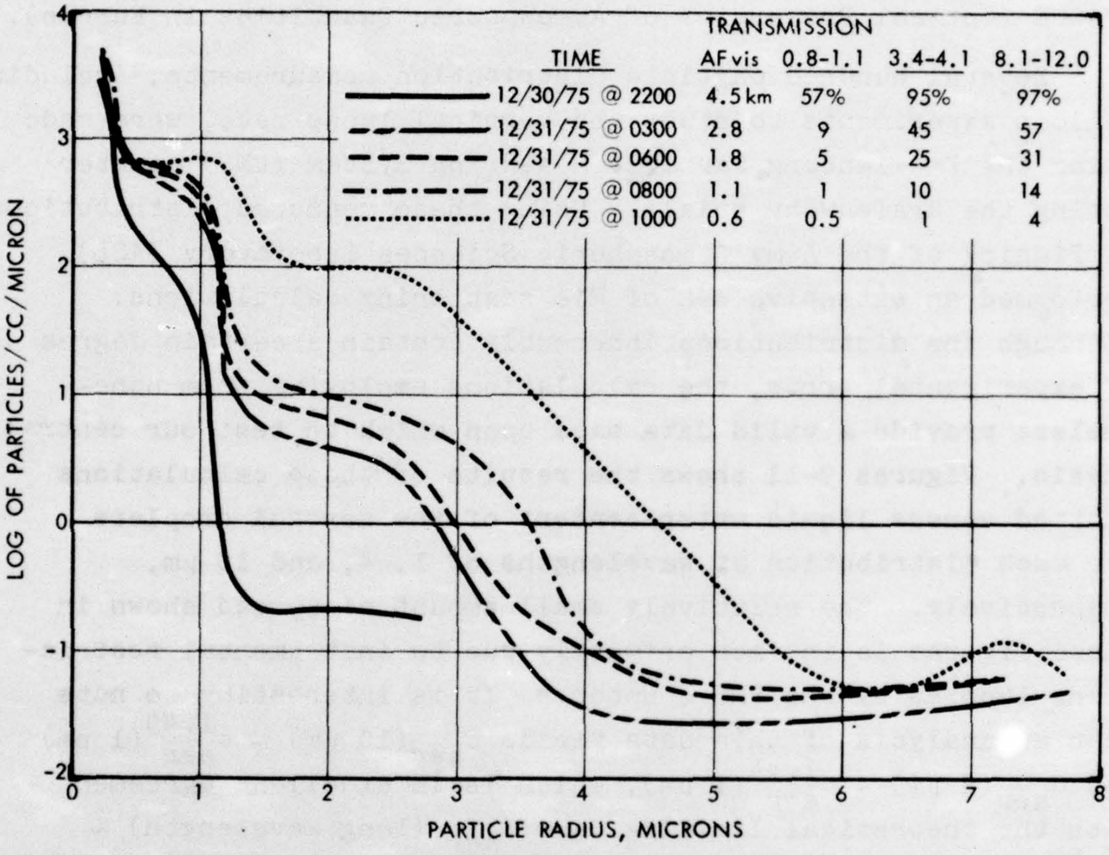


FIGURE 8. Growth of Aerosol Droplets as Fogs Build, December 30-31, 1975, at Grafenwöhr. Note that the left curve represents the best of the visibility, which is growing progressively worse with time and with the successive shifting of the curves to the right.

Present models in LOWTRAN merely increase the number density of the particles in the aerosol but do not change the distribution shape. This will be corrected in improved fog models growing out of both Grafenwöhr and NATO's atmospheric study entitled Project OPAQUE (Optical Properties of Atmospheric Quantities in Europe).

Several hundred particle distribution measurements, including balloon experiments to study the vertical lapse rate, were made using the Knollenberg Particle Measuring System (PMS) counter during the Grafenwöhr trials. Using these measured distributions, R. Pinnick of the Army Atmospheric Sciences Laboratory (ASL) performed an extensive set of Mie scattering calculations. Although the distributions inherently contain a certain degree of experimental error, the calculations employing them nonetheless provide a valid data base upon which to test our central thesis. Figures 9-11 shows the results of those calculations plotted versus liquid water content of the aerosol droplets for each distribution at wavelengths of 1, 4, and 10 μm, respectively. The relatively small amount of spread shown in these figures is in fact primarily due to instrumental restrictions imposed by the PMS counter.* It is interesting to note that an analysis of this data yields $\sigma_{aer}(10\ \mu m) \sim \sigma_{aer}^{1.49}(1\ \mu m)$ and $\sigma_{aer}(4\ \mu m) \sim \sigma_{aer}^{1.44}(1\ \mu m)$, which is in excellent agreement with the theoretical limiting case σ_{aer} (long wavelength) ~ $\sigma_{aer}^{1.50}$ (short wavelength) arrived at from considerations of the relationship of extinction coefficeint to volume. The conclusion of the above discussion is that the volume of particulate is in fact the most critical parameter in determining the aerosol extinction, and thus the scaling laws and subsequent analysis based upon our proposed method should be valid.

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*For example, depending upon the fog density, four different ranges of particle size were used. A mreasurement made using a given particle range on the equipment therefore necessarily excludes some particles otherwise measured using a different range setting. In general, the points clustered most tightly on a given line in Figs. 9-11 represent a single range setting for the instrument.

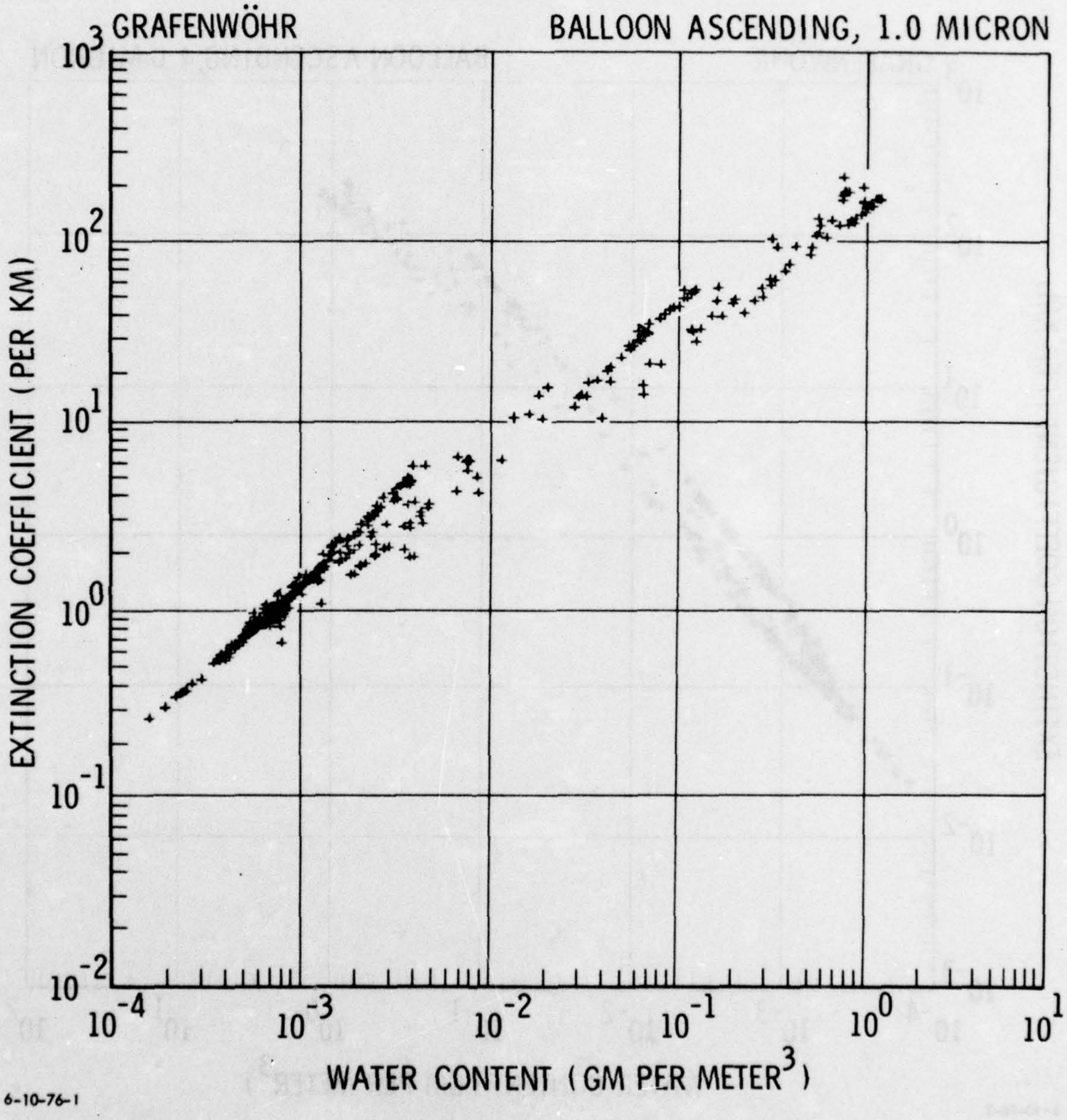


FIGURE 9. Comparison of Extinction Coefficient and Liquid Water Content of Aerosol Droplets

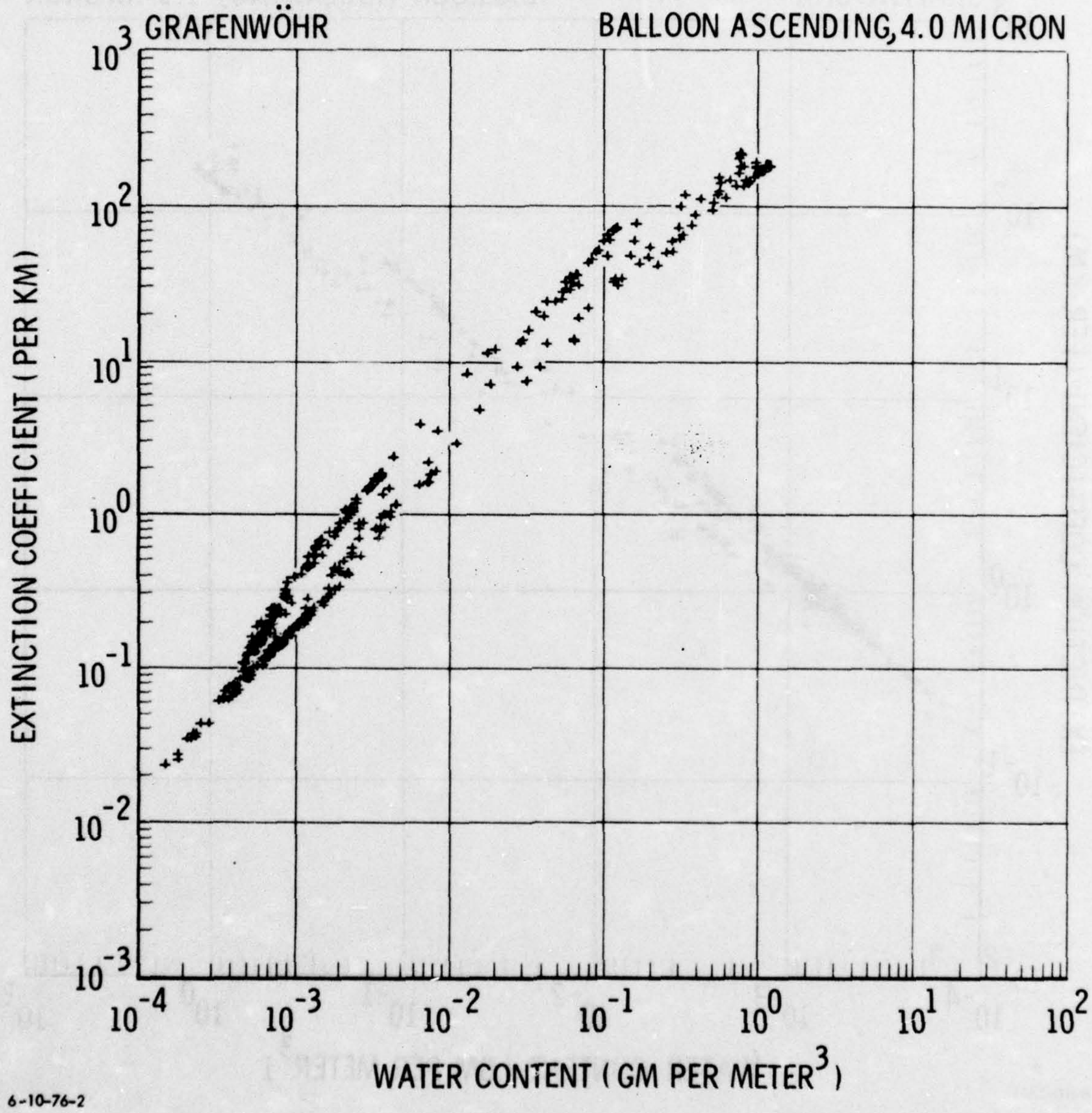
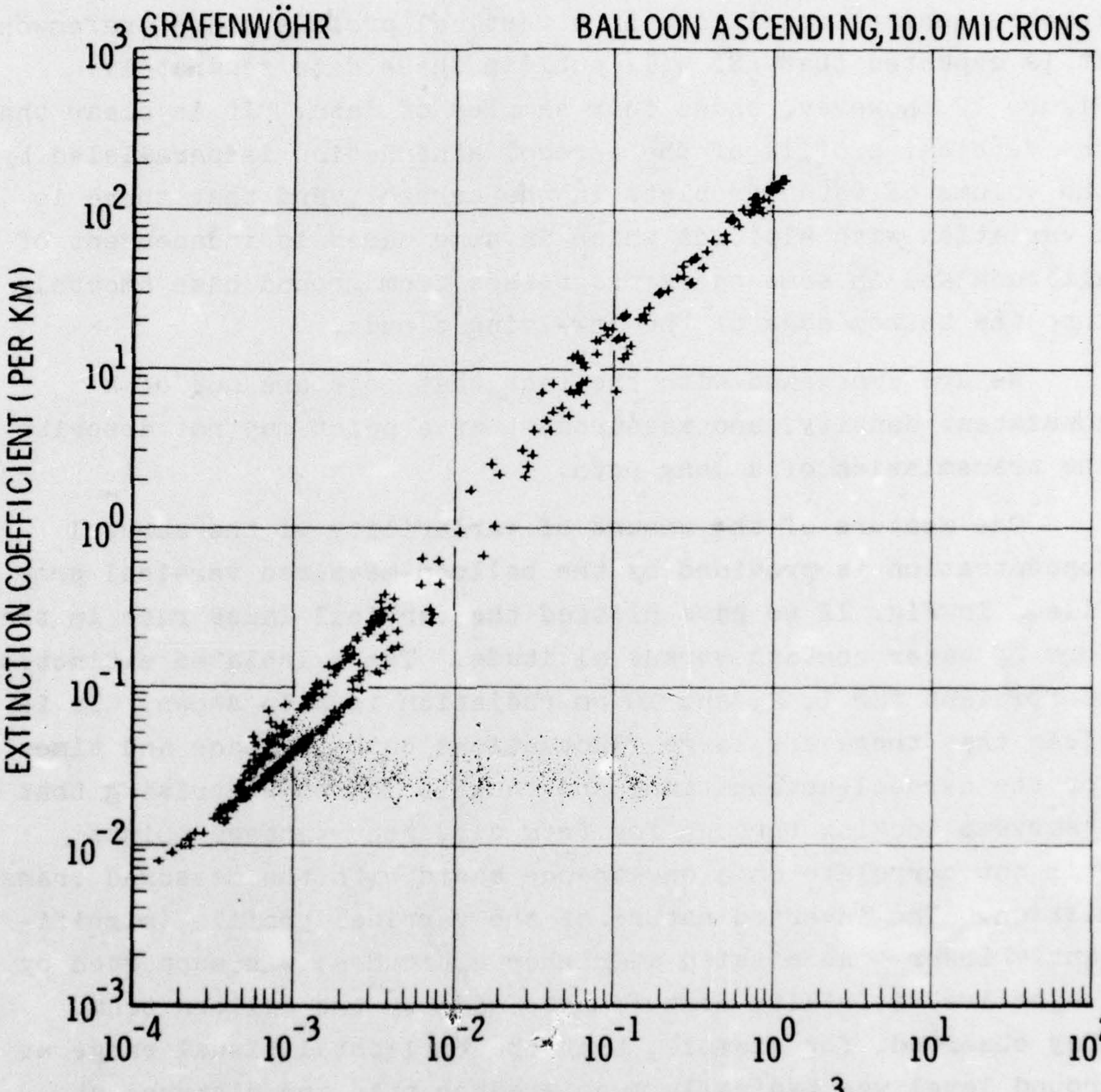


FIGURE 10. Comparison of Extinction Coefficient and Liquid Water Content of Aerosol Droplets



6-10-76-3

FIGURE 11. Comparison of Extinction Coefficient and Liquid Water Content of Aerosol Droplets

Based upon the balloon data and much similar material, R. Pinnick and his associates at ASL were able to calculate, using Mie theory, the extinction coefficients at a series of altitudes for the aerosol conditions in a vertical profile above Grafenwöhr. It is expected that ASL will publish these data separately. Figure 12, however, shows four samples of data. It is clear that the vertical profile of the aerosol attenuation is paralleled by the volume of water droplets in the aerosol, and that there is a variation with altitude which in some cases is independent of altitude and in some cases progresses from ground haze smoothly into the bottom edge of the low-lying clouds.

We are concerned with the fact that fogs are not of a consistent density, and measurement at a point may not describe the transmission of a long path.

One measure of the amount of variability of the aerosol concentration is provided by the balloon-measured vertical profile. In Fig. 12 we have plotted the vertical lapse rate in the form of water content versus altitude. The calculated extinction coefficient for 1, 4, and 10 μm radiation is also shown. It is clear that there are large fluctuations both in space and time for the aerosol attenuation, and thus it is not surprising that observers looking through fog from different vantage points will not correlate on a one-to-one basis with the measured transmission. The inverted nature of the vertical profile (significantly lower transmission at higher altitudes) was supported by subjective visibility measurements made by the balloon team. They observed, for example, that the horizontal visual range at ground level was typically much greater than the distance at which the balloon disappeared into the fog or haze. In general, the conditions on the ground to not necessarily represent the conditions at either a hundred feet or a few hundred meters. Since aerosol vertical profiles represent one of the major unknowns for low-flying aircraft missions, there is a real need for more measurements along these lines and for the subsequent formulation, testing, and verification of models to predict aerosol vertical profiles.

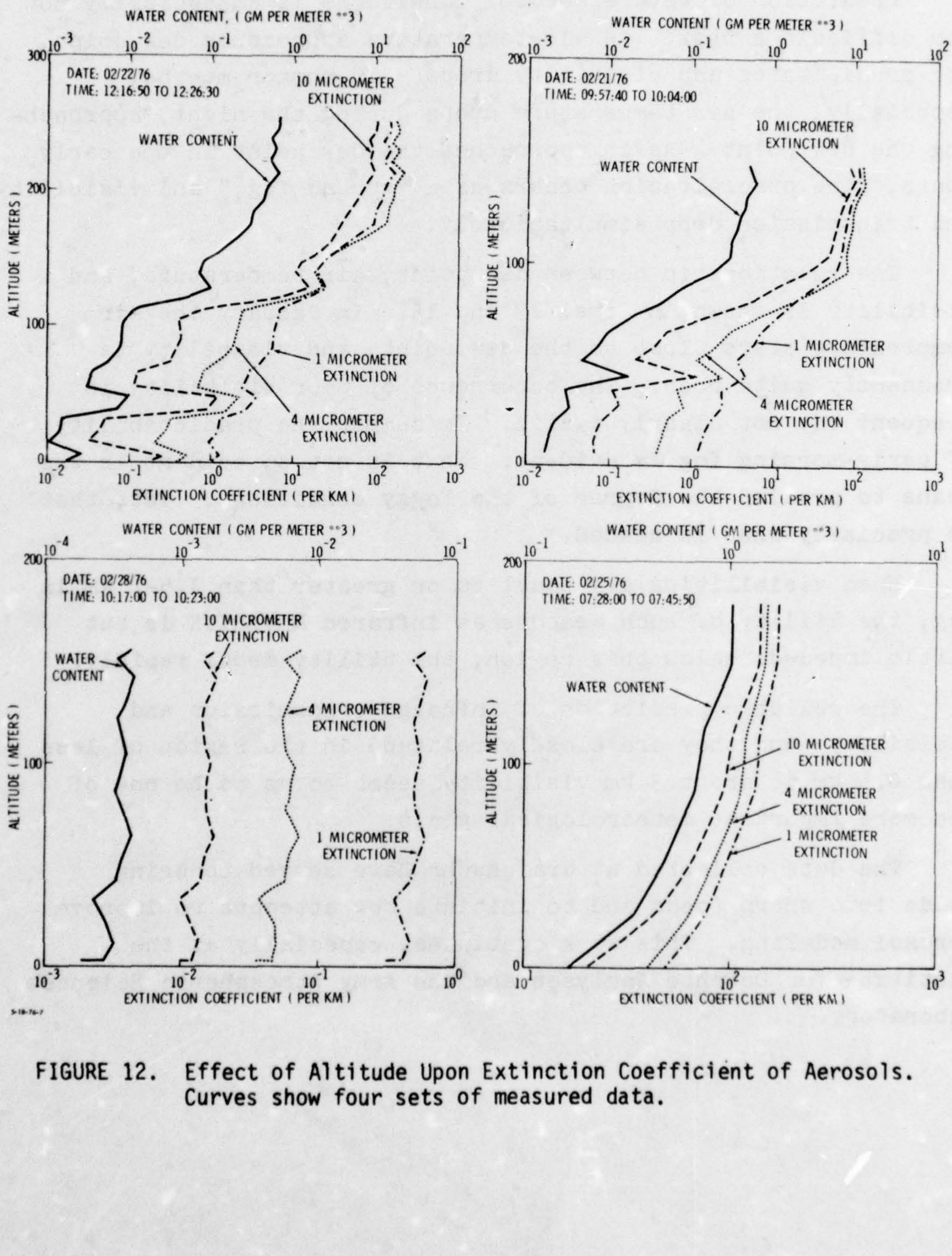


FIGURE 12. Effect of Altitude Upon Extinction Coefficient of Aerosols. Curves show four sets of measured data.

Prediction of severe aerosol conditions is conceptually not too difficult a task. As air temperature approaches dew point, fog precipitates and visibility drops. In summer months, especially, the air temperature drops during the night, approaching the dew point. As it approaches the dew point in the early hours, fine precipitation occurs as a "ground fog," and visibility and transmission drop simultaneously.

The relationship between dew point, air temperature, and visibility is shown in Figs. 13 and 14. In January the air temperature stays close to the dew point, and visibility is frequently quite poor. The occurrence of poor visibility is frequent but not clearly cyclic. In summer the predictability of early-morning fog is evident. What is not so evident is the means to predict the degree of the foggy conditions. Yet, that is precisely what is needed.

When visibilities are equal to or greater than 1.5-2 km in fog, the utility of such weapons as infrared MAVERICK is but little impeded; below this region, the utility drops rapidly.

The reliable prediction of infrared transmission and visibility (and they are closely related) in the region of less than 0.5 km to about 3 km visibility seems to us to be one of the more important meteorological goals.

The data collected at Grafenwöhr have served to bring needs into sharp focus and to initiate new attempts to improve aerosol modeling. This work continues, especially at the Institute for Defense Analyses and the Army Atmospheric Sciences Laboratory.

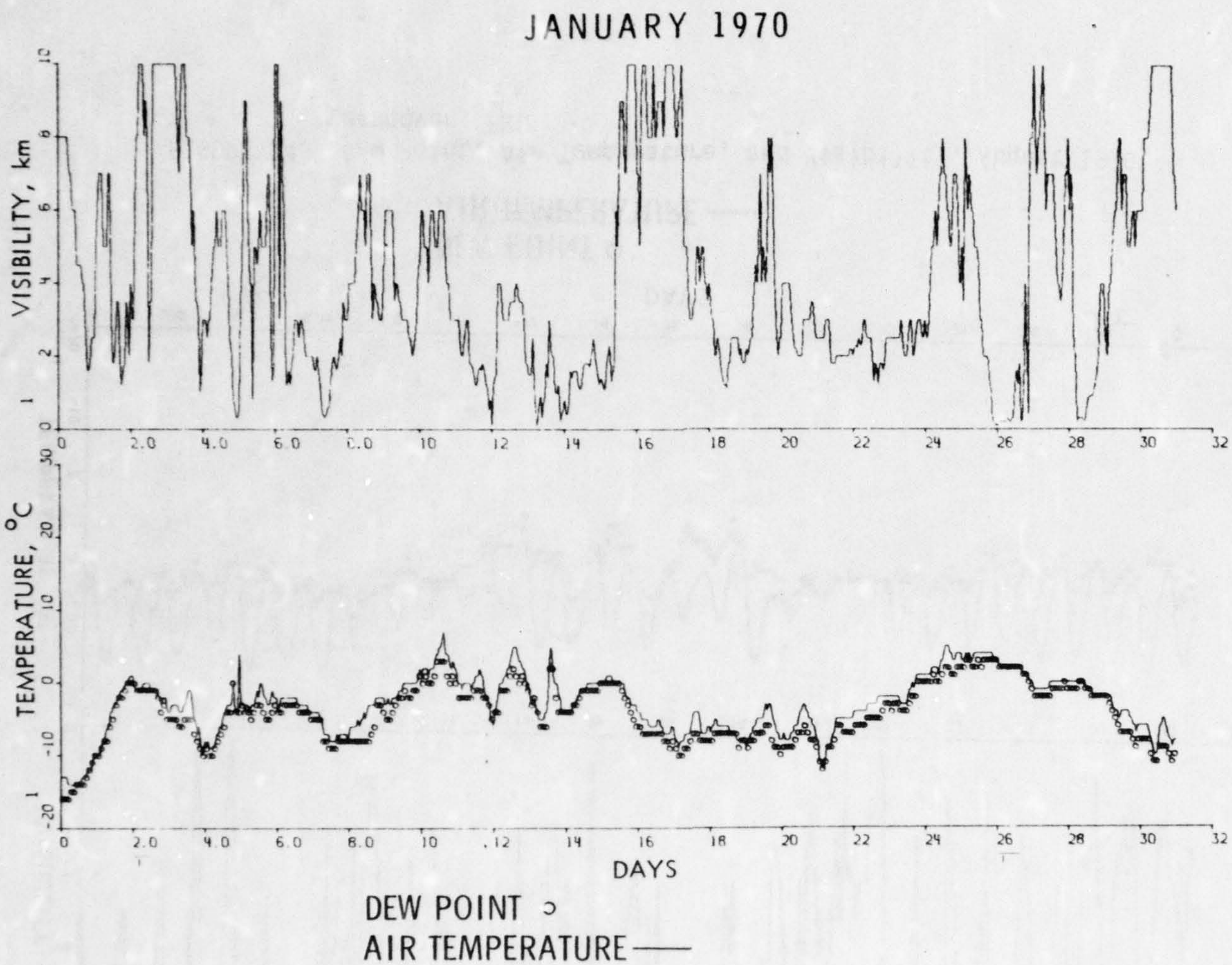


FIGURE 13. Dew Point, Air Temperature, and Visibility, January 1970, Hannover, FRG

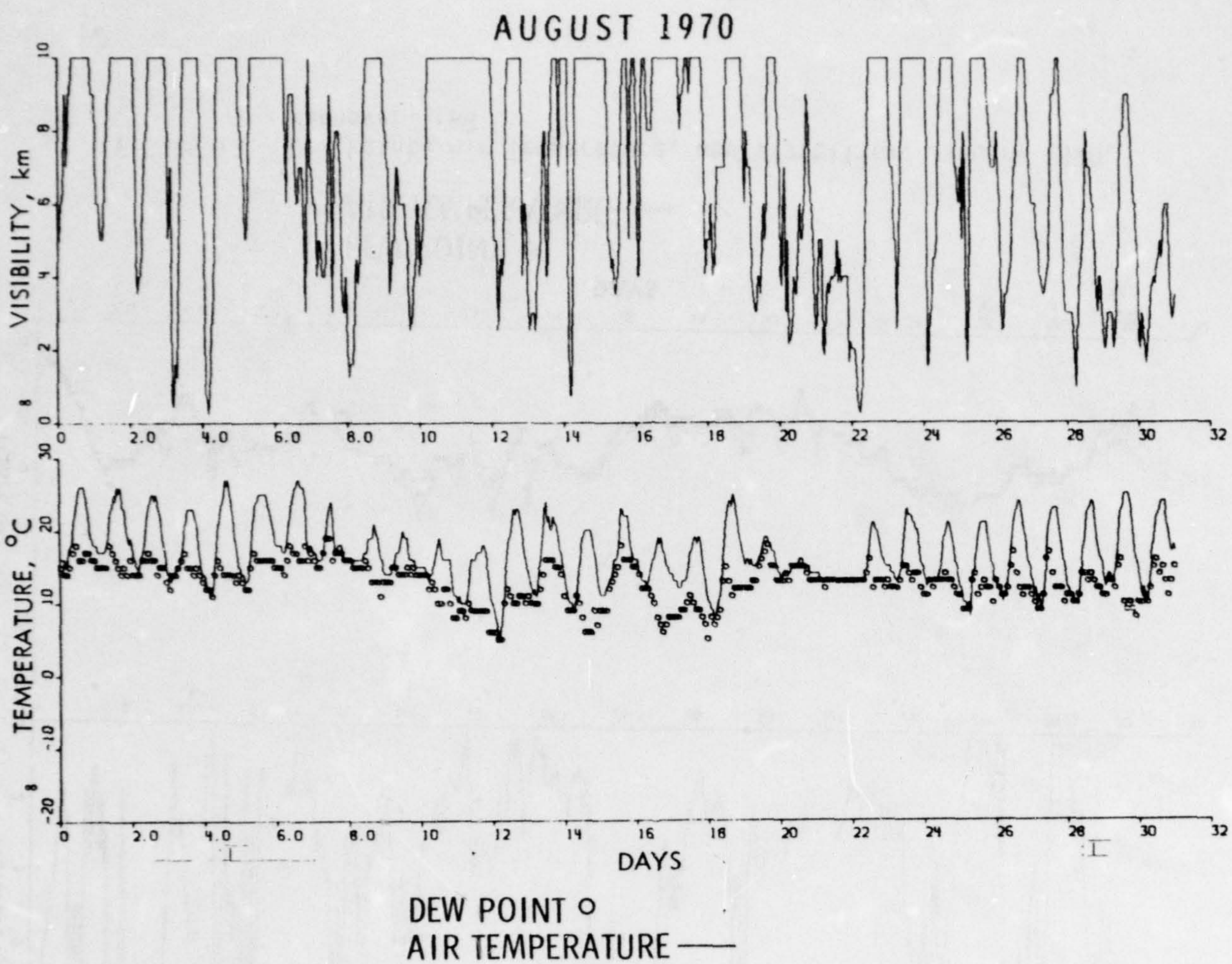


FIGURE 14. Dew Point, Air Temperature, and Visibility, August 1970, Hannover, FRG

V. STRENGTHS AND WEAKNESSES OF FIELD MEASUREMENTS OF ATMOSPHERIC TRANSMISSION

The Grafenwöhr trials and measurements of atmospheric transmission were probably one of the best sets of measurements carried out in the field that we know of. They were, however, not perfect. A number of problems directly related to the nature of the operation are unresolved. These are reviewed below.

Since many of the problems relate to calibration procedure and frequency, it is necessary to begin with a brief review of Moulton's methodology, which in principle is excellent, but which becomes less than ideal as the time between calibrations is allowed to become more than several days.

Several methods of calibration have been devised and used at the Army Night Vision Laboratory (NVL) with some degree of success. Of these methods, only the collimator method has been used extensively and is in current use by NVL, and therefore that is the only one discussed here. Unfortunately, all methods necessitate portability of part or all of the source end of the transmissometer system. This logistic burden, added to the delicate and technical nature of the system, results in calibration procedures that are challenging to carry out in field environments.

This calibration procedure uses the source end of the transmissometer as a collimator at near-zero distance from the receiver portion of the transmissometer. That is, the transmissometer source is removed from its normal far-field location and positioned immediately in front of the receiver. The entrance aperture of the source collimator optics is accurately aligned to insure that the entrance aperture of the receiver is fully

within the collimated beam of the source. The transmissometer system is operated similarly to normal-field operation except that an aperture setting is selected to provide an angular presentation of the collimated source similar in angular size to the source viewed during far-field operation.

Locating the collimated source to fall within the small field of view of the transmissometer receiver is best accomplished by physically aligning the receiver to "boresight" with the collimator. To begin, one starts with the longest aperture wheel setting on the collimator and pans the receiver slowly in azimuth and elevation until a high signal is obtained. One then reduces the aperture wheel and repeats the angular peaking process. This process is continued until the aperture size required for calibration is attained. At this point, all other controls should be adjusted for maximum output signal. If at anytime the output signal exceeds 100%, the transmission percentage gain potentiometer should be adjusted to reduce the value below 100%. Depending upon the transmissometer involved, the calibrator may find interaction between adjustment controls during the peaking process, and therefore continuing checks for a peak on all parameters are required.

Clearly, this method determines the signal strength from a relatively stable radiation source at effectively zero distance. Since this signal is huge compared to that obtained when the source and the receiver are one to several kilometers apart, the signal is throttled to a useful value by means of controlling apertures mounted on a wheel to allow ease of selection.

When the source and receiver are separated after calibration two things must hold for the measurements to be valid. The apertures must be precisely known, as their geometry is a direct control of the source output, and the source output together with the receiver sensitivity must be quite constant, or measured frequently enough that variations with time are noted by the

calibration process before the drift exceeds allowable measurement tolerances.

Because many channels were measured, the calibration procedure became a tedious process. The stabilization of the sources was slow so that the entire calibration procedure was time consuming, making it not only a nuisance but a time-consuming nuisance interfering with operations.

As a result, there were too few calibrations so that when instruments were repaired there were step functions--large step functions--in the data without calibrations to correct the questionable data.

Largely because of this sort of problem, we believe that we should at present confine our analysis to the 1180-meter data nearly along ground level as the most valid data set.

We believe one can correct the 4300-meter data from 125 feet above the ground to the ground (along a nearly horizontal path, because the ground sloped appreciably). This correction would be done by analogy rather than be based upon calibration data, which leads to suspiciously high values of transmission.

Further, we have considerable faith in our atmospheric modeling. It matches the 1180-meter data well, but when it is applied to the 4300-meter data there is a major discrepancy between modeled and measured data.

This sort of problem is even more prominent in the second phase of the tests, a situation that made it necessary for us to rely exclusively on modeled atmospheric transmission for the imaging phase of the trials.

The Grafenwöhr measurements also underline the need for extended flexibility in the selection of transmission path lengths. Even for the relatively low-visibility conditions encountered during this trial period, most of the infrared transmissions for the 1180-meter path were measured to be near 90%, with only a small effect due to aerosols. The result of making transmission

measurements near the 100% limit is that a large error is introduced into the derived extinction coefficient, which is the most relevant atmospheric parameter from the point of view of the sensor performance analysis. For example, using Eq. 1 for a measured transmission of 90% with a possible calibration error of 3% over a 1-km path, the extinction coefficient can assume values between 0.07 km^{-1} and 0.14 km^{-1}, a factor of 2 difference. For the same calibration error and a 10% measured transmission, the error introduced into the extinction calculation is a factor of 1.03. Since the calibration error is expected to remain constant for lower transmission values, it would therefore seem advisable to select substantially longer paths in order to lower the measured transmission and thus reduce the error in the resulting extinction coefficient. Unfortunately, this is only part of the story. As the transmission becomes lower so that the calibration error is reduced, a new error is introduced due to an overall loss of sensitivity. This results from the rapid geometric fall-off of light reaching the detector. For a specific radiometer and environment these kinds of arguments can be used to select optimal path lengths. For example, in the case of the Barnes radiometer, L. Ruhnke of the Naval Research Laboratory has shown that a minimization of errors due to both calibration and sensitivity leads to a selection of path lengths which differ by factors of about 10 independent of the environment. Unfortunately, the actual selection of paths is more often decided on the basis of strategic requirements (i.e., operational distances for tanks in a battlefield scenario) and/or geographical restrictions (i.e., terrain masking).

There are several off-the-shelf devices for measuring the particle concentration as a function of size, ranging from impactors to laser light-scattering instruments such as the ones employed at Grafenwöhr. Although none of these are expected to provide an accurate measure of the particle distribution for the variety of aerosols found in the field (solid and liquid),

the PMS counter is probably close to the state of the art for field measurements. We feel that the particle size distribution measurements made with the Knollenberg PMS instrument have the capability of yielding much useful information concerning the strong vertical lapse rate of the aerosol. In fact, the strong vertical inhomogeneity points to one of the primary inadequacies of our current atmospherics program: namely, the relationship between our normal ground-based meteorological measurements and slant-path image propagation. We believe that this problem could also be addressed directly by sampling the total amount of particulate along the various slant paths of interest rather than making the more sophisticated measurement of the entire particle size distribution.

VI. CONCLUSIONS AND DISCUSSION CONCERNING ATMOSPHERIC TRANSMISSION

1. Weather forecasting and collection activities must learn to predict the effects of aerosols in a manner which is more meaningful for atmospheric transmission and electrooptical sensor performance. The current techniques are compromised by a lack of versatility and reliability. A more useful method must either sample or estimate different portions of the atmosphere giving an indication of spatial inhomogeneities which are very important to the operational planning of electrooptical missions.

2. The collection of atmospheric data confirms that aerosols are the primary atmospheric limitation to electrooptical system performance. For medium to high visibilities our current atmospheric models such as the current LOWTRAN are probably adequate for predicting IR transmission. For these conditions the IR transmission in both the 3.4-4.1 μm and 8.1-12.0 μm regions are consistently high (near the molecular absorption limit), whereas the Si (near-visible laser and active TV bands) transmission is often degraded badly.

3. The effects of rain or wet snow do not seem to favor or penalize any band relative to another. As a first approximation to atmospheric transmission modeling for these conditions, one should adopt a simplistic "equal attenuation rule" for the visible and IR portions of the spectrum. Such a model is easily implemented with the usual visual range input.

4. Our current aerosol models suffer considerably (especially for fog conditions) from reliance upon a single or finite number of scaled particle size distributions. It is clear from the Grafenwöhr measurements that this methodology is not valid. Recognizing that the volume content of particulates along the transmission path is the most important parameter in determining the aerosol extinction justifies the use of more general scaling laws that are independent of the shape of the particle distribution.

5. There appear to be strong similarities between measured aerosol attenuation for the German winter measurements presented here and other vastly different environments (i.e., Southern English maritime and Camp A. P. Hill in Virginia). These similarities, if properly documented,* could be usefully exploited by those concerned with weather-sensor performance modeling.

*This conclusion, although not documented in this report, is the subject of another current IDA study.

REFERENCES

1. Institute for Defense Analyses, Infrared Continuum Absorption by Atmospheric Water Vapor in the 8-12 μm Window, IDA Paper P-1184, R. E. Roberts, L. M. Biberman, and J. E. A. Selby, April 1976.

2. J. E. A. Selby, E. P. Shettle, R. W. Fenn, R. A. McClatchey, and F. E. Volz, "Principles of the LOWTRAN 3 & 3a Models," Appendix A in Institute for Defense Analyses, Effect of Weather at Hannover, Federal Republic of Germany, on Performance of Electrooptical Imaging Systems, Part 1: Theory, Methodology, and Data Base, IDA Paper P-1123, L. M. Biberman, August 1976.

APPENDIX

PROCEDURES FOR DATA SELECTION

Table A-1, which illustrates a very small fraction of the data, shows a comparison between transmission measurements in the 8.1-12.0 μm band taken by the Army Night Vision Laboratory (NVL) at Grafenwöhr, FRG, and calculated transmission values for this band using an atmospheric transmission model (LOWTRAN). Atmospheric data which is required as input to the model was gathered at the same time by NVL at Grafenwöhr and is also shown in the table. LOWTRAN is a model developed by the Air Force Geophysics Laboratory (AFGL) and is documented well elsewhere.* Table A-1 includes 214 different hours of data, each denoted by a sequence number, taken during the period November 1975-January 1976 (the sequence is in chronological order). Table A-1 includes only those hours in which the weather conditions were clear to light fog. Weather conditions of rain and snow and medium to heavy fog have been reserved for later analysis.

LOWTRAN requires the following inputs: atmospheric pressure, relative humidity, temperature, path length, bandwidth, and visibility. For this table the path length was a constant 1.18 km and the bandwidth 8.1-12.0 μm. The pressure, relative humidity, and temperature were taken for a particular day and hour from NVL records of measurements at Grafenwöhr. Five different visibilities were used as inputs to LOWTRAN for each

*J. E. A. Selby and R. A. McClatchey, Atmospheric Transmittance from 0.25 to 28.5 μm: Computer Code LOWTRAN 3, Air Force Cambridge Research Laboratories, AFCRL-TR-75-0255 (7 May 1975).

TABLE A-1. COMPARISON OF MEASURED AND CALCULATED TRANSMISSION FOR THE 1180-METER PATH LENGTH

SEQUENCE NUMBER	3	5	7	11	14	18
DATE	11/27/75	11/27/75	11/27/75	11/29/75	11/29/75	11/29/75
TIME	1445	1830	2030	500	500	900
PRESSURE (MB)	958	958	957	948	948	950
TEMPERATURE (C)	-1.3	-1.6	-1.6	2.3	3.2	4.6
REL. HUMIDITY (PCT)	93	96	98	97	96	98
WATER VAPOR DENSITY (GM/M^3)	4.14	4.16	4.25	5.50	5.78	6.48
WEATHER TYPE (1A)[a]	--	--	--	--	--	CLER[b]
WEATHER TYPE (3A)[c]	HAZE	LTFG[d]	LTFG[d]	CLER[b]	CLER[b]	CLER[b]
VISIBILITY (KM):						
ASL[e]	2.5	5.0	5.0	5.0	7.0	20.0
AF[e]	3.7	2.8	3.7	4.7	7.0	11.2
SILICONE[e]	5.1	A[f]	A[f]	7.9	7.6	7.6
PHOTOPIC[e]	3.4	A[f]	A[f]	5.4	5.1	5.1
NON-AEROSOL[e]	4000.	4000.	4000.	4000.	4000.	4000.
TRANSMISSIONS:						
MEASURED	.78	.73	.72	.73	.73	.76
ASL LOWTRAN[e]	.76	.84	.83	.81	.83	.85
AF LOWTRAN[e]	.81	.78	.81	.81	.83	.84
Si LOWTRAN[e]	.84	A[f]	A[f]	.84	.83	.82
PHOTOPIC LOWTRAN[e]	.80	A[f]	A[f]	.82	.81	.80
NON-AEROSOL LOWTRAN[e]	.91	.91	.91	.89	.89	.87
EXTINCTION COEFFICIENT (KM^{-1}):						
MEASURED	.21	.27	.28	.27	.26	.23
NON-AEROSOL[e]	.08	.08	.08	.10	.10	.12
ESTIMATED AEROSOL EXTINCTION (KM-1)	.13	.19	.20	.17	.16	.11

[a] 1A = subjective estimate of NVL personnel at transmissometer site.

[b] CLER = clear.

[c] 3A = subjective estimate of ASL personnel along transmissometer path.

[d] LTFG = light fog.

[e] Term explained in text.

[f] A = not calculated.

particular day and hour. LOWTRAN was called five times to calculate five different transmission values, each based on a different "visibility" input. The first visibility used as an input to LOWTRAN was called "ASL visibility." This was the visibility that was directly observed at Grafenwöhr for that particular day and hour by the Army Atmospheric Sciences Laboratory (ASL). The transmission value obtained from this input is called "ASL LOWTRAN" in the table. The labels for the other transmission values obtained from LOWTRAN will be similarly designated. The second visibility input to LOWTRAN was the AF visibility. This was obtained from a measurement taken by the Air Force on the same day and hour at a weather tower near Grafenwöhr. Thirdly, the Si visibility was calculated from the silicon transmissometer data (0.8-1.1 μm band). The calculation was done as follows:

$$\text{Si visibility} = \ln 50/\sigma$$

where

$\sigma = (1/L) \times \ln(1/t)$

t = Si measured transmission

L = path length (1.18 km).

The photopic visibility, the fourth visibility, is the Si visibility multiplied by the constant 0.675. The fifth visibility is a constant 4000-km input to LOWTRAN to estimate a non-aerosol atmospheric condition as represented by an "infinite" visibility value.

Given all the above-mentioned measured data, several exclusion criteria were applied to separate the data into groups. The criteria applied were the following:

1. If no 8.1-12.0 μm band transmission data were collected at Grafenwöhr for a particular day and hour, the data for the entire hour were eliminated as no comparison could be made between measured and calculated data.

2. If no visibility data were collected by ASL at Grafenwöhr nor by the Air Force at the tower nearby, the data for the entire hour were eliminated due to insufficient data.

3. If either of the two weather reporting forms (1A and 3A) indicated snow or rain, the data for that hour were placed in a second group to be analyzed later.

4. If either weather reporting form (1A or 3A) indicated medium or heavy fog, the data for that hour were placed in a third group to be analyzed later.

5. If the Si (0.8-1.1 μm) measured transmission was less than one-half the HgCdTe (8.1-12.0 μm) measured transmission, the Si visibility and Si LOWTRAN transmission were not calculated. An "A" was entered in the table to indicate this.

6. If the HgCdTe (8.1-12.0 μm) measured transmission was greater than the non-aerosol LOWTRAN transmission, the date for that hour were eliminated.

7. If the HgCdTe measured transmission was less than the average of the ASL, AF, and Si LOWTRAN transmission minus 0.1, the data for that hour were eliminated. In the case where Si LOWTRAN transmission was not calculated (see item 5 above), the Si LOWTRAN transmission was not included in the average.

Out of a total of 678 hours of data, 214 were left in the first group, 154 were put into the snow and rain group, 54 were put into the medium and heavy fog group, and 256 were eliminated.